

# On the Emergence and Discovery of Hot Spots in Supernova Remnant 1987A <sup>1</sup>

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## ABSTRACT

We present the discovery of several new regions of interaction between the ejecta and equatorial circumstellar ring of SN1987A, an interaction leading to a much expanded development of the supernova remnant. We also trace the development of the first such “hot spot,” discovered in 1997, back to 1995. Later hot spots seem to have emerged by early 1999. We discuss mechanisms for the long delay between the first and later spots.

*Subject headings:* circumstellar matter — ISM:individual (SNR 1987A) — supernova remnants

## 1. INTRODUCTION

The development of SN 1987A provides an unprecedented opportunity to observe, at high spatial, spectral, and temporal resolution, the birth of a supernova remnant (SNR). Observations of SNR 1987A might reveal the angular and velocity distribution of the ejecta by highlighting where it impacts a presumably well-known nebular structure. While SNR 1987A has been observed for some years in X-rays and radio, only optical/near-IR data have sufficient sensitivity and angular resolution to detail the structures presented here.

The early discovery of these interaction regions is crucial. We demonstrate how they are best revealed with difference imaging, in  $H\alpha$  and  $[N II]$ , and in He I  $1.083\mu m$ , for which

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<sup>1</sup>Based in part on archival observations obtained with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc. under NASA contract NAS5-26555.

the newly-formed spots have greatest contrast above the circumstellar equatorial ring (ER). We detect several new interaction sites, and trace known features back to epochs well before their actual discoveries.

## 2. OBSERVATIONS AND REDUCTIONS

As the contrast between the first hot spot and the underlying ER was greater in He I  $1.083\mu\text{m}$  than in optical lines at early times (§3), we have conducted ground-based monitoring of the ejecta-ER collision in this line. Data were taken on the CTIO 4-m Telescope with Tip-Tilt first order wavefront correction, on 5 nights between 1997 November and 1998 October [days 3926–4243 after SN core collapse] with the CIRIM imager [1.75 h total integrations] and 1999 December 25 [day 4688] with the OSIRIS imager/spectrometer [3.5 h total integration]. To accurately measure small changes in the ER and hot spot fluxes, we apply image subtraction techniques (Tomaney & Crofts 1996) as briefly outlined below. We also deconvolve images from each epoch, using multiscale maximum entropy (Pantin & Starck 1996) to improve the FWHM to  $\sim 0''.3$ .

We also analyze data from the *HST* public archive, making use of: a) STIS spectra (G750M grating) from 1997 April 26 [day 3715] and 1998 November 14 [day 4283]; b) NICMOS images taken through F108N on 1997 December 9 [day 3942]; and c) WFPC2 images taken through F336W, F439W, F555W, F656N, F658N, F675W, and F814W between 1994 February and 1999 April [days 2537–4440]. Pipeline calibrated STIS spectra were taken directly from the archive, while the NICMOS dither pattern was manually re-mosaiced. For PC chip images, aberrant pixels were replaced, and multiple exposures were co-added with cosmic-ray rejection. Recent press-release images from Kirshner et al. (2000)<sup>4</sup> are highly

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<sup>4</sup>STScI-PR00-11 available at <http://opposite.stsci.edu/pubinfo/pr/2000/11>

deconvolved, an invasive procedure which is sensitive to the input PSF and the stability of the pixel map. Furthermore, subtraction of deconvolved images assumes that constant sources are mapped identically in each epoch. To study hot spot variability, we opted for the non-iterative, non-invasive procedure of PSF-matched difference imaging. The PC chip has a PSF FWHM  $\sim 1.7$  pixels, below Nyquist critical sampling, so we first convolved images with a circular gaussian of  $\sigma = 0.65$ , smoothing to a final FWHM  $\gtrsim 2.2$  pixels. Registered, convolved frames were then PSF matched, photometrically scaled, and differenced using *difimphot* calls to IRAF routines (e.g. *immatch*). All flux calibrations used standard *HST* methods.

### 3. DISCUSSION

We propose to denote known and future hot spots as, e.g. HS 1-029, where the first digit represents the order of discovery and the trailing three digits encode the first reported imaging PA of the feature. This scheme preserves the order of appearance and provides a rough spatial location. Names based solely on discovery order will become confusing as new knots appear at a higher rate. The PA encoding is approximate; different passbands and data quality will naturally show small PA differences.

*Discovery of New Hot Spot Activity:* The highest quality image (Figure 1a) from our ground-based He I monitoring (1998 October 6 with a FWHM =  $0''.71$ ) shows the ER and the first hot spot (HS 1-029) resolved between Stars 2 and 3. Figure 1b displays a difference between 1999 and 1998 images. While the continued brightening of HS 1-029 is obvious, a second spot (HS 2-104) has now appeared—the first new locus of activity (Bouchet et al. 2000) since the discovery of HS 1-029 in 1997 April spectra (Pun et al. 1997). Figure 1c presents a deconvolution of the 1999 December image, with a final FWHM =  $0''.34$ . Several regions of brightening are distributed around the ER. Such low-level deconvolution features

require confirmation, seen below with *HST* images.

Figure 1d shows a 1997 December 11 NICMOS F108N mosaic with FWHM =  $0''.10$ . Star 5 and HS 1-029 are clearly resolved on the ER, with no other hot spots significantly detected. The ratio of F108N flux from HS 1-029 to the total ER+HS 1-029 flux is  $0.06 \pm 0.01$ . The same ratio from 1998 February 6 WFPC2 imaging is  $0.03 \pm 0.01$  for both F656N and F675W, and is  $0.02 \pm 0.01$  for F502N in 1997 July 10. Since F656N and F675W imaging followed the F108N epoch by nearly two months while HS 1-029 was brightening rapidly, *at early times* hot spots appear at greater contrast above the ER in He I  $1.083 \mu\text{m}$  than in strong optical transitions, as found in ground-based data (Kunkel et al. 1998). We recommend diligent monitoring of the ER in He I, with adaptive optics and with a resuscitated NICMOS, to detect new hot spot activity promptly.

*Confirmation in Archival HST Data:* As reported by Lawrence & Crotts (2000), a STIS G750M/6581Å spectrum from 1998 November shows the spectroscopic signature of a developing hot spot. The  $0''.2$  wide slit was positioned at PA  $102^\circ 9$ , and includes HS 2-104 and perhaps a fraction of HS 4-091. As Figure 1e shows, a wide-velocity feature, with FWHM  $\sim 150 \text{ km s}^{-1}$ , is redshifted from the ER at this position by  $\sim 50 \text{ km s}^{-1}$ , correcting for the displacement between the slit center and HS 2-104. This feature’s flux is  $\sim 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$  in  $\text{H}\alpha$ . This is similar in description to HS 1-029 on the near side of the ER, seen in 1997 April by Sonneborn et al. (1998), blueshifted over the range  $0\text{-}250 \text{ km s}^{-1}$ . With a measured  $\text{H}\alpha$  flux of  $\sim 1.0 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ , HS 1-029 on day 3715 appears more developed than HS 2-104 on day 4283.

Following our ground-based discovery of new spot activity, HS 2-104 and four other new spots were promptly detected in STIS F28X50LP and WFPC2 F656N imaging (Maran, Pun, & Sonneborn 2000; Garnavich, Kirshner, & Challis 2000). As HS 2-104 was detectable in archival *HST* spectra, we reviewed the public STIS, NICMOS, and WFPC2 data to search

for the earliest appearances of all spots. No spots other than HS 1-029 and HS 2-104 were seen in the STIS or NICMOS archives, and HS 2-104 appeared only in the STIS spectra from 1998 November described above. Figure 1f displays the F656N difference image between 1999 April and 1998 February. All of the five “new” spots are detected, along with at least three more sites of increasing F656N flux along the ER inner edge. All recently discovered activity began *no later than 1999 January* [day 4337]. The positions, fluxes, and earliest detections of nine spots, measured in the F656N 1999–1998 difference image relative to the centroid of SN 1987A in F656N in 1994 February, are presented in Table 1 ( $\pm 3^\circ$  in PA,  $\pm 0''.03$  in  $r$ , and  $\pm 10\%$  in flux for the first four,  $\pm 30\%$  for the rest). The first eight spots are also detected in 1999-1998 F675W differences. There are also marginal detections of new spots at ( $166^\circ$ ,  $0''.51$ ) and ( $183^\circ$ ,  $0''.48$ ), but these are faint and seen in only one epoch.

Known and unknown transient hot pixels contaminate roughly 1% of the PC chip, and since most of the WFPC2 imaging of SN1987A was not spatially dithered within filter sets, these pixels present a persistent, stochastic and non-gaussian source of noise, to which both difference imaging and deconvolution analyses are precariously sensitive. A full presentation of our analysis technique will be presented in a subsequent paper. Briefly, we cosmetically correct known bad pixels, while tracking their redistribution through the convolution and registration processes. To minimize false detections, a potential hotspot (residual in a difference image) must not lie within a bad-pixel domain and must appear in at least two difference images between mutually-exclusive data. The dashed arrow in Figure 1f indicates a “false” spot caused by a bad pixel. Newly detected spots should be considered tentative until they have been confirmed with further imaging or spectroscopic data, e.g. HS 7-289 is confirmed in STIS spectra from 2000 May 1 (Lawrence, Sugerman, & Crotts 2000). The remaining unconfirmed spots could also be reverse-shock  $H\alpha$  emission at low velocity (Sonneborn et al. 1998; Michael et al. 1998).

*The Evolution of HS 1-029:* Figure 2 shows difference images for seven WFPC2 bands spanning optical wavelengths. Each row portrays a single filter, and each column the differences between a given year and 1994. Orientation is indicated by the inset graphic. The 1994 images have been scaled down to match the fading ER, in order to highlight flux changes on this structure. As such, residuals from field stars remain, notably for Star 5. The evolution of HS 1-029 is clearly demonstrated. Although first reported in STIS spectroscopy from 1997 April, HS 1-029 is clearly detectable in 1996 February in F502N, F555W, F675W, and F658N, and is seen faintly in F555W and F675W in 1995 March. The spot is evident in 1996 even in differences without PSF matching. HS 1-029 began developing *on or before 1995 March* [day 2933].

A large arc of transient flux brightens after 1994 in F675W, F656N, and F658N. First noted by Garnavich & Kirshner (1996), it spans  $180^\circ < \text{PA} < 235^\circ$  in F675W and nearly encircles the ER in F658N in 1996. Relative fluxes in these filters in 1996 and 1997 suggest it is mostly [N II] emission. This could be limb-brightened recombination near the base of the bipolar lobes, where the walls of the “hourglass” join with the ER (Crotts, Kunkel, & Heathcote 1995). A lower density implies a long delay before maximum intensity, consistent with line-emission models of Lundqvist & Fransson (1991), and a peak in 1998 indicates a density  $\sim 10$  times lower than in the ER. Continued monitoring in [N II] could reveal additional hourglass structure.

#### 4. CONCLUSIONS

HS 1-029 began within 8 years after the SN and at least 3–4 years ahead of the subsequent spots. Did this asymmetry arise in the velocity of the ejecta, in the density of the blue supergiant (BSG) wind, or in the morphology of the ER itself? The BSG wind should have been azimuthally smoothed by rotation of the progenitor, and relatively undisturbed by the

ER (interior to the reverse shock  $\sim 5 \times 10^{17}$  cm from the star). Rayleigh-Taylor instabilities are expected in this decelerating wind, however over the  $\sim 20000$  yr age of the ER (Crotts & Heathcote 1991) the sound speed would have allowed smoothing of these over scales of tenths of a parsec. This should be modelled over timescales for the BSG wind propagation to the ER ( $\sim 1000$  yr). If the ER/ejecta interaction asymmetry were due to a large-scale misalignment between a bipolar ejecta pattern and the ER axis, a counter-jet should have impacted opposite HS 1-029, contrary to observation. It seems likely that the asymmetry is due to structures in the ER or ejecta velocity field with fairly narrow extent in position angle, i.e. thin fingers or jets. The homogeneity of the ER's shape versus the long delays between the HS 1-029 and later spots points to the ejecta velocity field as the major cause.

Valuable opportunities to obtain diagnostic spectra of the hot spots at very early times have been lost. If the fainter spots presented here are confirmed, then the ejecta have reached the ER over a wide range of PAs, and soon little pristine ER material will remain. Frequent ground and space-based monitoring of this rapidly developing event is required, with emphasis on difference imaging in He I  $1.083\mu\text{m}$ ,  $\text{H}\alpha$ , and  $[\text{N II}]$ .



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Fig. 1.— (a) A He I  $1.083\mu\text{m}$  ground-based image of SNR 1987A from 1998 October. (b) A He I difference image between 1999 December and 1998 October. New activity centered on HS 2-104 is indicated. (c) A deconvolution of the 1999 December He I image. (d) A NICMOS F108N mosaic from 1997 December. Frames a–d are  $6''$  square with north up, east to the left. (e) A STIS 52X0.2 G750M spectrum centered at  $6581\text{\AA}$ ,  $5''.0$  wide and  $36\text{\AA}$  tall with slit at  $\text{PA} = 283^\circ$ .  $\text{H}\alpha$  from HS 2-104 is indicated. (f) A difference between WFPC2 F656N images from 1999 April and 1998 February,  $3''.0 \times 2''.0$  with north up, east to left. Radial lines indicate the PAs of the hot spots, which are located slightly outwards from the inner segment. The dashed arrow flags a bad pixel residual.

Fig. 2.— An array of WFPC2 difference images with 1994 subtracted from 1995–1999. Each row presents a particular filter, noted to the left; the first frame in the F656N row is F658N. Each column shows a given year, subtracted by 1994, noted at top. Each frame is  $2''.1 \times 2''.3$  with north indicated by the graphic. The 1994 images have been scaled down to match the mean ER emission; regions fading relative to 1994 appear black. Note that HS 1-029 began as early as 1995 March in F555W and F675W.

Table 1. Hot Spots in SNR 1987A.

Spot	PA (°E of N)	$r$ (")	$\Delta f_{99-98}$ <sup>a</sup> ( $10^{-17}$ erg cm <sup>-2</sup> s <sup>-1</sup> )	$t_{earliest}$ <sup>b</sup> (days)	Refs.
1-029	27	0.56	425	2933	1
2-104	106	0.68	62.1	4283	2
3-126	123	0.60	58.1	4337	3
4-091	91	0.68	30.8	4337	4
5-139	139	0.54	9.5	4337	4
6-229	230	0.67	1.2	4440	4
7-289	289	0.64	2.3	4440	5
8-064	64	0.61	9.3	4440	6
9-075	75	0.64	6.8	4440	6

<sup>a</sup>Flux difference in F656N between 1999 Apr and 1998 Feb, scaled so that fading ER emission cancels.

<sup>b</sup>Earliest detection in *HST* data, days after SN.

References. — (1) Pun et al. 1997; (2) Bouchet et al. 2000; (3) Maran et al. 2000; (4) Garnavich et al. 2000; (5) Lawrence et al. 2000; (6) first reported here.



